# Radar Reconnaissance of Near-Earth Objects at the Dawn of the Next Millennium

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## I. IN'1'RO1)IICTION

Radar, the most powerful groundbased technique for post-discovery investigation of NEOs, can contribute a great deal to their exploration as well as to identification and mitigation of hazardous objects. My intentions in this article are to review the current state of NEO radar reconnaissance, examine the imminent prospects for this work as upgraded instrumentation becomes available, and propose construction of a next-generation radar telescope that, unlike any existing radar instrument, would be optimized for, and dedicated to, NE() radar.

## II, TECHNIQUES

Radar is uniquely capable, of resolving NEOs spatially by measuring the distribution of echo power in time delay (range and Doppler frequency (line-of-sight velocity) with very fine precision in each coordinate, as shown in Table 1. Delay-Doppler images provide otherwise unavailable information about the h-u-get's physical properties, including size, shape, rotation, multiplicity, near-surface bulk density and roughness, and internal density distribution (Ostro 1993).

The delay-Doppler projection is somewhat counter-intuitive and is subject to global aliasing, but given adequate orientational cove.rage, an imaging sequence can be inverted to yield a detailed, unambiguous model of the target (Hudson 1993). Hudson has calibrated the accuracy of the "reconstruction inversion" with his laboratory laser radar (Andrews et al. 1995), which serves as a scaled-down model of the Arecibo (13-cnl, 2380-MHz) and Goldstone (3.5-cm, 8510-MHz) asteroid-imaging radars. (The inversion is a lot like the template-fitting process used to generate radar maps of Venus from groundbased or spacecraft delay-Doppler im ages.)

Additional remote-sensing advantages accrue from radar wavelengths' sensitivity to near-surface bulk density and roughness. For comets, radar waves can penetrate optical] y opaque comas to examine the nucleus and can also disclose the presence of macroscopic coma particles.

The fractional precision of delay-l~oppler positional measurements plus their orthogonal ity to optical astrometry makes them invaluable for refining orbits and prediction ephemerides (Yeomans and Chodas 1994). A single radar detection secures the orbit well enough to prevent "loss" of the object, shrinking the object's instantaneous positional uncertainties by orders of magnitude with respect to an optical-only orbit and greatly improving the accuracy of long-term trajectory predictions (Yeomans et al. 1987, 1992). During the past two decades, observations of NEOs (Ostro et al. 1991a) have revealed range errors from ~100 km to -100,000 km in pre-radar range predictions.

## 111. HIGHLIGHTS OF NEO RADAR RESULTS

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Echoes from 38 NEAs (see list at http://echo.jpl.nasa.gov/) have furnished new information about these objects' physical and dynamical properties, Reflectivity y and polarization signatures reveal striking diversity in NEA characteristics. Asteroid 61'78 (1986 DA) is significant y more reflective than any other radar-detected asteroid; it may be a 2-km, highly nonconvex (bifurcated?) piece of NiFe metal derived from the interior of a much larger object that melted, differentiated, cooled, and subsequently was disrupted in a catastrophic collision (Ostro et al. 1991b). At the other extreme, the radar signature of 1986 JK suggests a surface bulk density within a factor of two of 0.9 g $cm^{-3}$ (Ostro et al. 1989). Similarly, NEA circular polarization ratios, a measure of the severity of small-scale roughness, range from ~ 0.1 (e.g., 1685 Toro and 1989 JA) to 1.0 (2.101 Adonis and 1992 QN); see Ostro et al, 1991 a, references therein, and Benner et al. 1996.

Radar observations of six comets have provided useful constraints on nuclear dimensions, spin vectors, and surface morphologic. The echoes from comet IRAS-Araki-Alcock, which came within 0.03 AU of Earth in 1983 (Harmon et al. 1989; Goldstein et al. 1984), show a narrowband component from the nucleus as well as a much weaker broadband component attributed to large particles ejected mostly from the sunlit side of the nucleus. Models of the echoes suggest that the nucleus is very rough on scales larger than a meter, that its maximum overall dimension is within a factor of two of 10 km, and that its spin period is 2-3 days. The particles are probably sever-al centimeters in size and account for a significant fraction of the particulate mass loss from the nucleus. Most of them appear to be distributed within ~1000 km of the nucleus, in the volume filled by particles ejected at several meters per second over a few days. Radar spectra of comet Halley (Campbell et al. 1989) are broad and show no hint of a component as narrow as that expected from the nucleus, whose dimensions and spin vector were constrained by Giotto and Vega spacecraft images. The echo's bandwidth and radar cross section suggest that it arises predominantly from coma particles with radii >2 cm. The nondetection of Halley's nucleus implies a surface with a very low bulk density. Echoes from the **coma** of comet 1996132. Hyakutake (Fig. 1) are about ten times stronger than those from the nucleus, whose size probabl y is about 2 km (1 Iarmon et al. 1996).

observations of 1620 Geographos (Ostro et al. 1995a, 1996) yield -400 images with ~100-m resolution (Fig. 2). The pole-on silhouette.'s extreme dimensions are in a ratio, 2.76 ± 0.21, that establishes Geographos as the most elongated solar system object imaged so far. The images show craters as well as indications of other sorts of large-scale topographic relief, including a prominent central indentation. Protuberances at the asteroid's ends may be related to the pattern of ejecta removal and deposition caused by the asteroid's gravity field.

A sequence of delay-Doppler images of 4769 Castalia (I 989 PB) (Fig. 3; Ostro et al. 1990), obtained two weeks after its Aug. 1989 discovery, reveal it to consist of two kilometer-sized lobes in contact. Least-squares estimation of Castalia's three-dimensional shape (Fig. 4) from the radar images supports the hypothesis that Castalia is a contact-binary asteroid formed from a gentle collision of the two lobes and also constrains the object's surface morphology and pole direction (Hudson and Ostro 1994).

Delay-Doppler imaging of4179 Toutatis in Dec. 1992 (Ostro, et al. 1995b) achieved resolutions as fine as 125 ns (19 m in range) and 8.3 mHz (O. 15 mm/s in radial velocity), placing hundreds to thousands of pixels on the asteroid. The images reveal this asteroid to be in a highly unusual, non-principal-axis (NPA) spin state with several-day characteristic time scales. This data set provides physical and dynamical information that is unprecedented for an Earth-crossing object. Hudson and Ostro (1995) used a comprehensive physical model to invert the lower-resolution images (Fig. 5) to estimate, the asteroid's shape and inertia tensor, initial conditions for the asteroid's spin and orientation, the radar scattering properties of the surface, and the delay-Doppler trajectory of the center of mass. Figure 6 shows four views of the low-resolution model that show shallow craters, linear ridges and a deep topographic "reck" whose geologic origin is not known. It may have been sculpted by impacts into a single, coherent body, or Toutatis might actually consist of two separate objects that came together in a gentle collision. Toutatis is rotating in a long-axis mode (Fig. 7) characterized by periods of 5.41 days (rotation about the long axis) and 735 clays (average for long-axis precession about the angular momentum vector). The asteroid's principal moments of inertia are in ratios within 3% of 3.19 and 3.01, and the inertia tensor is indistinguishable from that of a homogeneous body. Such information has yet to be determined for any other asteroid or comet, and probably is impossible to acquire in a fast spacecraft fl yby. Higher-resol ution images (e.g., Fig. 8) from the 1992 experiment are now being used to refine the Toutatis model.

## IV. PHYSICAL STUDIES OF NEOS USING RADAR-BASED MODELS

Accurate shape models of near-}iarth asteroids open the door to a wide variety of theoretical investigations that previously have been impossible or have used simplistic models (spheres 01 ellipsoids). For example, with detailed models of real objects, it is possible to explore the evolution and stability of close orbits, with direct application to the design of robotic and piloted spacecraft missions, to studies of retention and redistribution of impact ejecta, and to questions about plausible origins and lifetimes of asteroidal satellites.

Scheeres et al. (1995, 1996a) have used the Castalia and Toutatis models to investigate close-orbit dynamics around these objects. For each body, both stable and unstable periodic orbits exist as closed orbits in an asteroid-fixed frame. The fate of material launched from the surface is a strong function of initial velocity and surface location, Return, escape, periodic, and realistic landing orbits about these objects have been rendered (e.g., Fig. 9) and animated by de Jong and Suzuki (1996). Similar studies (Scheeres et al. 1996b) are exploring close orbits about 433 Eros using radar-based models (Mitchell et al. 1996).

Radal--derived models also allow realistic investigations of the effects of collisions in various energy regimes on the object's rotation state, surface topography, regolith, and internal structure. Simulations of impacts into Castalia using, smooth particle hydrodynamics code have begun to suggest how surface and interior damage depends on impact energy, impact location, and the equation of state of the asteroidal material (Asphaug et al, 1996). These computer investigations have clear ramifications for our understanding of asteroid collisional history, for exploitation of asteroid resources, and eventually for deflection/destruction of objects found to be on a collision course with Earth.

## V. CAPABILITIES OF CURRENT RADAR TELESCOPES

The Arecibo Observatory (Fig. 10) has just undergone a major upgrade and about to resume normal operations. By 1997 it will be more than 20 times as sensitive as Goldstone, see twice as far, and cover three times as much volume. The more fully steerable Goldstone instrument (Fig. 11), with a solid angle window twice the. size of Arecibo's and an hour-angle window at least several times wider than Arecibo's for any given target, will serve a complementary role, especially for new] y discovered objects.

Table 11 lists the radar-astrometric range limits expected for Arecibo and Goldstone by 1997. Goldstone also can be used as the transmitter in a bistatic configuration with the 27-antenna Very Large Array (VLA) as an aperture-synthesis receiver (de Pater et al. 1995). The G-VLA system can measure angular positions of NEAs with uncertainties that approach 0.01 arcsec, or an order of magnitude finer than the best optical astrometry.

Table 111 lists statistics of NEA opportunities at Arecibo as a function of signal-to-noise ratio (SNR) achievable on a single date, before and after the upgrade and also after a "Spaceguard Survey" of the NEA population (Morrison 1992). (Comet radar opportunities are very roughly 10% as frequent as NEA opportunities. SNRS >20 are quite adequate for detection and marginal resolution of the echoes. SNRs >100 let one achieve enough resolution to be able to make simple statements about shape, and data sets with SNRS >1000 can reveal geologic features. SNR increases as the square root of the integration time and can be expected to be of the same order as the number of useful imaging pixels and the number of parameters in a shape reconstruction, The highest-SNR radar investigations can be as informative as the cheapest NEO flybys under consideration. It is not exaggerating to claim that in principle, radar is to physical characterization of asteroids as the Hubble Space Telescope is to physical characterization of the rest of the Universe.

## VI. RADAR AND THE NEO EXPLORATION STRATEGY

These *Proceedings* are based on a conference that was co-sponsored by the Explorers' Club. Exploration of new frontiers energizes the human spirit -- it is an antidote to the human condition. It serves as a vehicle for international cooperation and is important to the future of human civilization. But exploration of space, which truly is the final frontier, is also horribly expensive. For economic reasons alone, those NEAs whose orbits make them the cheapest targets of robotic or piloted space missions arc destined to be central to our future in space.

A cost-effective. NEO exploration strategy can be visualized as a pyramid whose layers represent efforts that become more informative, more expensive, and less widely applied toward the top. Optical search programs are the pyramid's foundation. Above them are optical astrometric follow-up efforts and the infrastructure for orbit and ephemeris calculation, and then physical and chemical characterization by VIS/IR/UV techniques. Radar's attributes and limitations place it between other groundbased efforts and robotic space missions, which include numerous cheap flybys and then, higher up, rendezvous missions (orbiters, landers, sample-returns). The pyramid is topped by missions with human crews.

Radar can lower the risk and cost of space missions by making interplanetary navigation easier and by providing *a priori* characterization of the target. For example, the Goldstone imaging of Geographos in August 1994 (Ostro et al. 1996) was given special impetus by the Clementine mission, which planned a 10.7 km/s flyby of Geographos on Aug. 31 at a miss distance of approximated y 100 km (Nozette and Garrett 1994). We planned to use radar astrometry to improve the pm-encounter ephemeris and to use imaging to optimize the post-encounter physical model of the asteroid, Although a computer malfunction led to cancellation of the flyby, the Goldstone experiment provided practice for supporting future spacecraft reconnaissance of near-Earth asteroids. Before the observations, the asteroid's positional error ellipsoid had a typical overall dimension of ~11 km. Ranging on Aug. 28-29 and a preliminary shape model collapsed the ellipsoid's size along the line of sight to several hundred meters; its projection toward Clementine on its inbound leg would have been 11 x 2 km (D. K. Yeomans, pers. comm.). Goldstone-VLA plane-of-sky astrometry could have, shrunk the error ellipsoid's longest dimension to about 1 km, about half of Geographos's shortest overall dimension.

The experience, with Geographos and a similar one with 6489 Golevka (1991 JX; Ostro et al. 1995b) suggest that with adequate radar reconnaissance, it would be possible for a spacecraft lacking onboard optical navigation to be guided into orbit around, or collision course with, an asteroid. Even if on-board "opnav" capability were available, radar would nonetheless shrink the navigation uncertainties significantly, perhaps reducing the mission's fuel requirements enough to allow a larger mass budget for science instrumentation. Indeed, the U. S. Department of Defense is planning a follow-up mission, Clementine II (Hope et al. 1996), that will fly by three NEAs on dates that in each case follow Arecibo/Goldstone radar opportunities.

## VII, RADAR AND THE IMPACT HAZARD

One of the far-reaching motivations for surveying and exploring asteroids and comets is the impact hazard (Morrison et al. 1994). Radar can reduce both kinds of post-discovery uncertainty about potential catastrophic NEO collisions: orbits and physical properties (Ostro 1994). As demonstrated in "Table IV, the uncertainty in a newly discovered NEO's position years or decades in the future can be hundreds of times smaller if radar astrometry is available.. Golevka, the example in that table, was observed exhaustively with radar again in 1995 (Ostro et al. 1995c) and is known to make no dangerously close approaches to Earth for at least seven centuries (D. K. Yeomans, pers. comm.). But imagine a prediction that in 25 years a 500-m asteroid (a 10,000-megaton impactor, at the small end of the range of estimates for the transition from local devastation to global catastrophe) will miss Earth by 1 ± 30 lunar distances. That prediction would generate much more anxiety than, say, the report in spring 1996 that Eros might collide with Earth in a few million years (which garnered a full-page headline in the Apr. 25, 1996, *New York Times*), or the claim several years ago that comet Swift-Tuttle might hit the Earth on Aug. 14, 2126; see the cover story in the Nov. 23, 1992, *Newsweek*).

In fact, cislunar misses by objects 500 m or larger occur at average intervals of about 18 years. A Spaceguard Survey would discover ~6400 such objects (~70% of the ~9200 in the population). One of those objects passes one lunar distance from Earth once every 25 years on average, so four such events per century are likely to be predicted after a Spaceguard Survey. However, uncertainties in the predictions may not permit confident distinction of close-call trajectories from impact trajectories. Assessment of the danger would be dramatically more efficient and more reliable if radar astrometry were available to shrink the uncertainties (Yeomans and Chodas 1994). The availability of radar measurements could easily be the difference between knowing that an object will pass "within several Earth-Moon distances of Earth" in a few decades and knowing that it will "hit the Earth."

Whereas the warning time for an asteroid impact in the post-Spaceguard era is likely to be at least a century and hence more than adequate for mitigation at a comfortable pace, the warning time for an impact by a long-period comet (LPC) would probably be less than one year. Moreover, LPC trajectory extrapolation will be hampered by obscuration of the nucleus and by uncertainties about nongravitational forces, both of which increase as a comet approaches the inner solar system. For example, Chodas (1996) found that had comet Hyakutake (which missed Earth by 39 lunar distances) been on a collision course with Earth, the predicted close approach distance would have exceeded one Earth radius until just one month before impact.

Cislunar approaches by LPCs to within can be expected every few centuries. The uncertainty in trajectory extrapolation after discovery of these, objects could be terrifying, and any number of panic scenarios are possible. A prediction of a comet or asteroid impact might provoke an economically or psychologically destructive societal response, even if the predicted collision were known to be insufficiently energetic to affect the global ecology. Such a prediction could lead to hasty and costly development of a mitigation system whose existence would in itself introduce a significant risk to civilization (Sagan and Ostro, 1993). Society will surely want to reduce uncertainties associated with predictions of extremely close approaches of NEOs. Radar astrometry could provide insurance against false alarms. In the event of certain prediction of a collision, radar characterization of the threatening projectile would lend valuable support to the mitigation effort.

Fortunately, the odds against a globally catastrophic NEO collision are very large. The most likely outcome of a Spaceguard Survey will be that no object will turn out to be hazardous during at least the next century. Regardless of the outcome, the survey will identify tens of thousands of small worlds that, at least for a century, are not on collision course with Earth. The potential promise of these "friendly" NEOs is highly significant for a variety of reasons, most of which stem from their closeness to Earth and their accessibility (see chap. 11 of Shoemaker et al. 1995). As noted in Table 111, thousands of NEOs discovered in a Spaceguard Survey would be detectable at high SNRs. However, it will be difficult to take advantage of most of the radar opportunities summarized in that table. Radar usage of Arecibo, historically less than 5% (vs. ~75% for radio astronomy and -20% for ionospheric science), is unlike] y to rise above 10%. The Goldstone 70-m antenna, DSS-14, which has the transmitter, is part of NASA's Deep Space Network, which exists for spacecraft telemetry; the antenna's total radar astronomy usage is unlikely to rise above - 5%. Neither Arecibo nor Goldstone were optimized for NEO radar.

Over the next decade, it will become increasingly clear that most of the NEO reconnaissance that is technically achievable with Arecibo and Goldstone is precluded by the limited accessibility of those instruments, and that a dedicated NEO radar instrument is desirable. In this light, it seems appropriate to begin to assess the potential design, cost, and value of such an instrument.

## V] 11. A DEDICATED NEO RADAR TELESCOPE FOR THE NEW M11,1 ENIUM

From preliminary studies carried out at J]']. (G. Resch, pros. comm.), it appears that an ideal NEO radar telescope would probably consist of two large, fully steerable antennas (like the 100-m NRAO Greenbank Telescope now under construction in West Virginia; see http://www.gb.nrao.edu/GBT/), one for transmitting and one for receiving, separated by a few tens of kilometers, operating at a wavelength between 0.9 and 3.5 cm (Ka and X band). A two-antenna (bistatic) configuration obviates the frequent transmit/receive alternation required in single-antenna observations of NEOs -- the roundtrip travel time (RTT) of the signal between the radar and the target in seconds is numerically nearly equal to the target's distance in mAU, e.g., 10 seconds for a target 0.01 AU away. Advantages of a two-antenna telescope for NEOs include:

1. no on/off switching of the transmitter, which ages klystron amplifier tubes
2. no interruption of data acquisition or of coherent integration
3. no interruption of orientational coverage
4. no switching of antenna pointing between transmit and receive directions, which can differ by more than a beamwidth for a rapidly moving target
5. doubled data integration time
6. accessibility of arbitrarily close targets, including those within a few Earth-Moon distances (RTT < 10 s), using same configuration as for distant targets

The capital cost of this system, as calibrated by the experience with the GBT, would be within 10% of $180M, comparable to the cost of a Discovery mission. (Three such systems suitably spaced in longitude and latitude to ensure constant visibility of any part of the sky could be built for less than the cost of one launch of the Space Shuttle.)

Since this instrument would be dedicated to NEOs, it would compile more NEO observation time in one year than Arecibo and Goldstone could in a decade. Given the current state of the art of antennas, receivers and transmitters, it could be an order of magnitude more sensitive than the upgraded Arecibo telescope. The telescope's lifetime would probably be at least several decades, during which it would do flyby-level science (delay-Doppler imaging placing thousands of pixels on the target, over enough orientations to allow three-dimensional reconstruction of the shape. in geological detail) of over a thousand of the optically discoverable NEAs, as well as several-hundred-pixel imaging (and several-hundred-parameter shape reconstruction) of a few hundred mainbelt asteroids, not to mention orbit-securing follow-up astrometry on many thousands of newly discovered NEOs. The scientific return on this investment would be extraordinary.

This radar telescope could be built and operational in a decade. By then, the pool of radar-accessible NEAs would allow radar imaging at a level adequate to produce a useful 3-D model of a different asteroid almost every day. The radar images, movies, and models could be made available on the World Wide Web in real time, allowing nearly global participation in the excitement of the radar flybys. Ten years into the next millennium, a first-time encounter with a newly discovered, nearby world could be part of the daily experience of the average person in most of the countries of the world.

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**Table 1: Radar measurement Precision**

| | Range (meters) | Line-of-Sight Velocity (meters/sec) |
|---|---|---|
| Best Radar Resolution | ~1o | 0.0001 |
| Asteroid "size" | ~1 000 | 0.01 to 1 |
| Asteroid "location" | ~10 000 000 000 | 10000 |

**Table 2: Range limits (AU) for radar astrometry of New NEOs, corresponding to a single-date SNR 0120 and telescope sensitivities expected by 1997.**

| Asteroid Diameter | Arecibo | Goldstone |
|---|---|---|
| 10 m | 0.043 | 0.016 |
| 100 m | 0.10 | 0.041 |
| 1 km | 0.'24 | 0.10 |
| 10 km | 0.59 | 0.24 |

**Table 3: NIX) Radar opportunities with (IIC Upgraded Arecibo Telescope**

| | Number of objects with a single-date SNR greater than | | | |
|---|---|---|---|---|
| | 20 | 100 | 1000 | 5000 |
| Near Earth Asteroids | | | | |
| Annual average before upgrade (using actual statistics since 1980) | 3 | 0.9 | 0.3 | 0.1 |

| | | | | |
|---|---|---|---|---|
| Annual average after upgrade (using current NEA pool) | 10 | 6 | 2 | 0.6 |
| Annual average after Spaceguard Survey | | | | |
| (lower bounds) > 1 km | 80 | ?.0 | 10 | 4 |
| > 300 m | 160 | 80 | 2.0 | "1 |

**Table 4: Effect of Delay/Doppler Measurements on Extrapolation of the Orbit of 6489 Golevka (1991 JX) from Discovery-Apparition Astrometry***

| | Positional Uncertainty | | |
|---|---|---|---|
| Dataset | kilometers | Earth radii | lunar distances |
| Optical | 8,000,000 | 1260 | 21 |
| Optical + Radar | 25,000 | 4 | 0.07 |

*Uncertainties in the asteroid's April 2019 position predicted from 54 optical measurements from May 9 to July 3 are in the top row. The bottom row gives uncertainties for a prediction that includes 24 delay-Doppler measurements from June 5-15. (D. K. Yeomans, pers. comm.)

## FIGURE CAPTIONS

1. Echo power spectrum from comet 1996112 Hyakutake. See. Harmon et al. 1996.

2. Delay-Doppler images of asteroid 1620 Geographos (Ostro et al. 1996). The resolution is 0.5 μs x 1.64 Hz (75 m x 87 m). These frames are multi-run sums of co-registered images within twelve independent, 30°-wide rotation-phase blocks. The view is along the pole and the asteroid has the same rotational orientation in each frame, but the direction to the radar is different in each frame. In the top row, the asteroid-to-radar vector points toward 12 o'clock in the far left image (frame 1), toward 11 o'clock in the next image (frame 2), etc.

3. Radar images of asteroid 4769 Castalia (1989 PB). This 64-frame Arecibo "movie" is to be read like a book (left to right in the top row, etc.). The radar lies toward the top of the figure in the image plane, which probably is about 35° from the asteroid's equator. In each frame, echo power (i.e., the brightness seen by the radar) is plotted vs. time delay (increasing from top to bottom) and Doppler frequency (increasing from left to right). The radar

i] lumination comes from the top of the figure, so parts of the astei oid facing toward the bottom are not seen in these images. 'l'he object, each of whose lobes is about a kilometer in diameter, is seen rotat ing through about 220° during the 2,.5-h sequence. These images have been smoothed from the original resolution of 2. µs x 1117 (0.3 x 0.17 km). (Ostro et al. 1990, copyright 1990 by the AAAS.)

4. Three-dimensional computer model of asteroid 4769 Castalia (1 989 PB), derived by Hudson and Ostro (1994) from the radar images in Fig. 3. The object is about 1.8 km across at its widest. 'l'he effective resolution of the reconstruction is about 100 m. The left column uses the estimated radar backscattering law, the. center column uses a realistic optical scattering law and a Sun-asteroid-viewer angle of 37°, and the right column shows a wire-grid representation with surface contours at 3° intervals. in each column the renderings are 90° of rotation phase apart.

5. Radar images of asteroid 4179 Toutatis from 1992. Goldstone low-resolution images from Dec. 2-18 (top three rows) and Arecibo images from Dec. 14-19 (bottom row) are plotted with time delay increasing toward the bottom and Doppler frequency increasing toward the left. On the vertical sides, ticks are 2 µs apart. Two horizontal sides have ticks separated by 1117, for Goldstone and 0.28 Hz for Arecibo; those intervals correspond to a radial velocity difference of 18 mm/s. (Ostro et al. 1995, copyright 1995 by the AAAS. )

6. Computer model of asteroid 41'79 Toutatis from radar images in Fig. 5. The object's dimensions along the principal axes are 1.92, 2.40, and 4.60 km. The resolution of the computer model is about 84 m. (Hudson and Ostro 199S, copyright 1995 by the AAAS.)

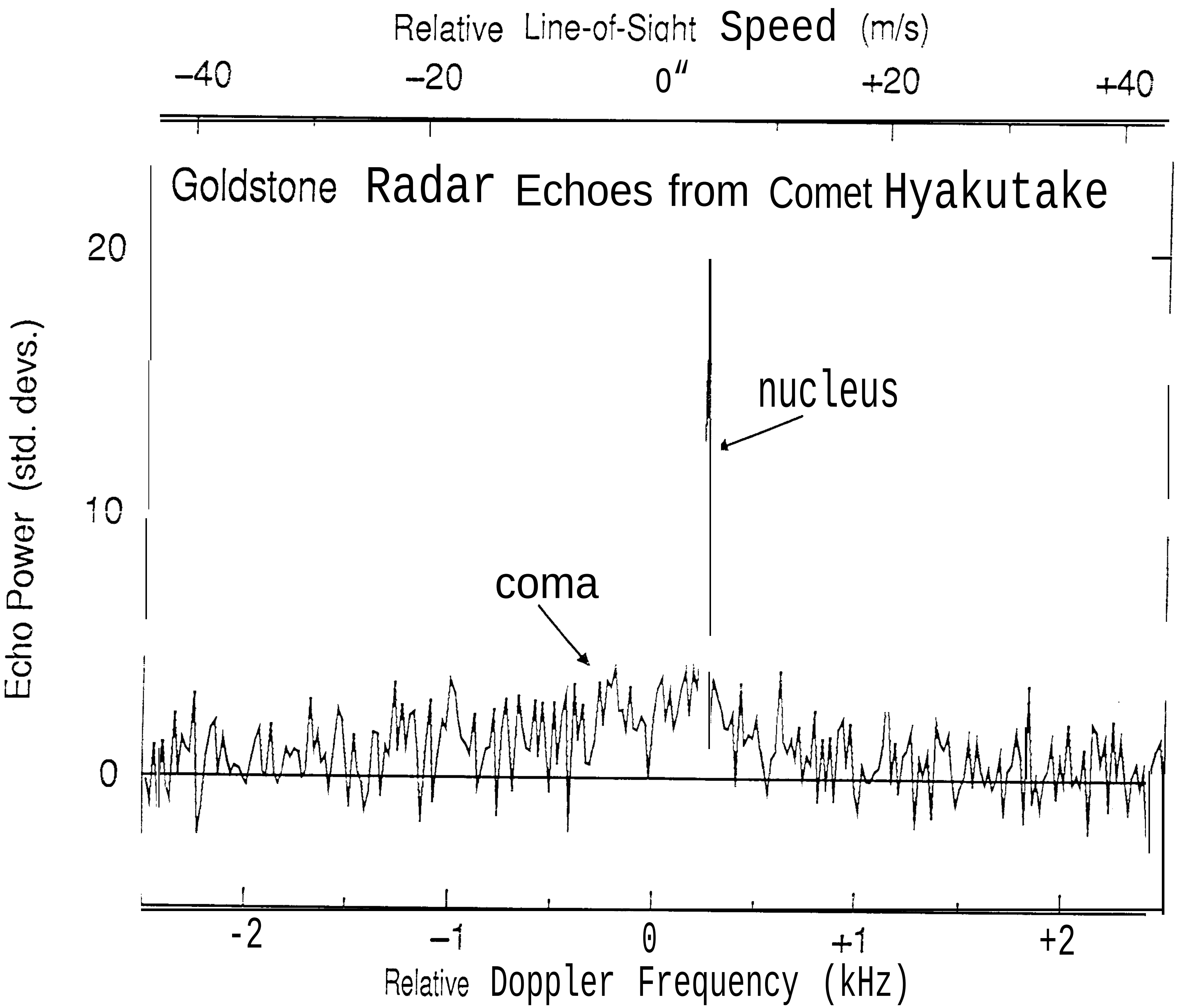
7. Spin state of Toutatis from the Hudson-Ostro (1995) modeling of radar images. Here the wh ite contours on the asteroid's surface arc loosel y analogous to an equat or and 0° and 90° meridians. Red, green, and blue axes are the object's short, intermediate, and long principal axes of i ncrt i a. The violet arrow is the angular momentum vector, and the yellow arrow is the instantaneous spin vector. The small spheres trace the path in an inertial frame of a point on the red axis at 1 S-minute intervals for 20 days into the future.

8. A high-resolution Goldstone image of Toutatis from Dec. 8, 1992, dilated according to km/Hz conversion factors predicted by the Hudson-Ostro (1995) model for the asteroid's spin state, with look-to-look translational smearing removed according to the model-based estimates of the trajectory of the asteroid's center of mass with respect to the delay-Doppler prediction ephemerides. Geometry is as in Fig. 5. Perimeter ticks are 1 km apart, (Ostro et al. 1995, copyright 1995 by the AAAS.)

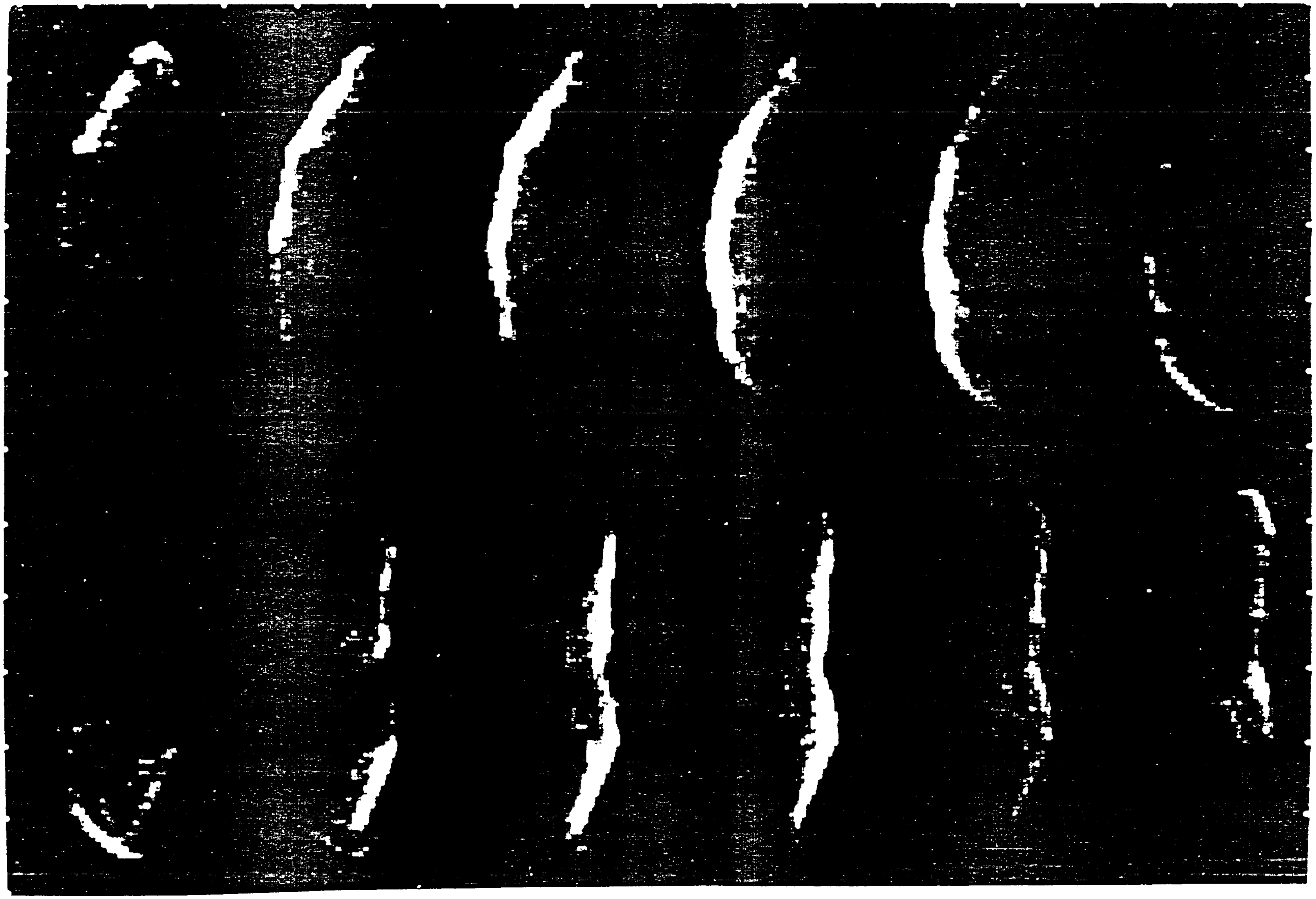
9. Return orbit about asteroid 4769 Castalia, calculated by Scheeres et al. (1996) using the Hudson-Ostro (1994) radar-based model, The particle was launched at 0.2 m/s and returns 1.4 days later at 0.2 m/s. This is one frame from a library of animations of close orbits around Castalia (dc long and Suzuki 1996).

**10.** The 305-m Arecibo telescope in Puerto Rico, **a.** Aerial view. **b.** Feed platform, which is suspended -170 m above the main reflector. 'l'he 26-m-diameter radome encloses the new Gregorian feed assembly and radar transmitting/recei ving equipment

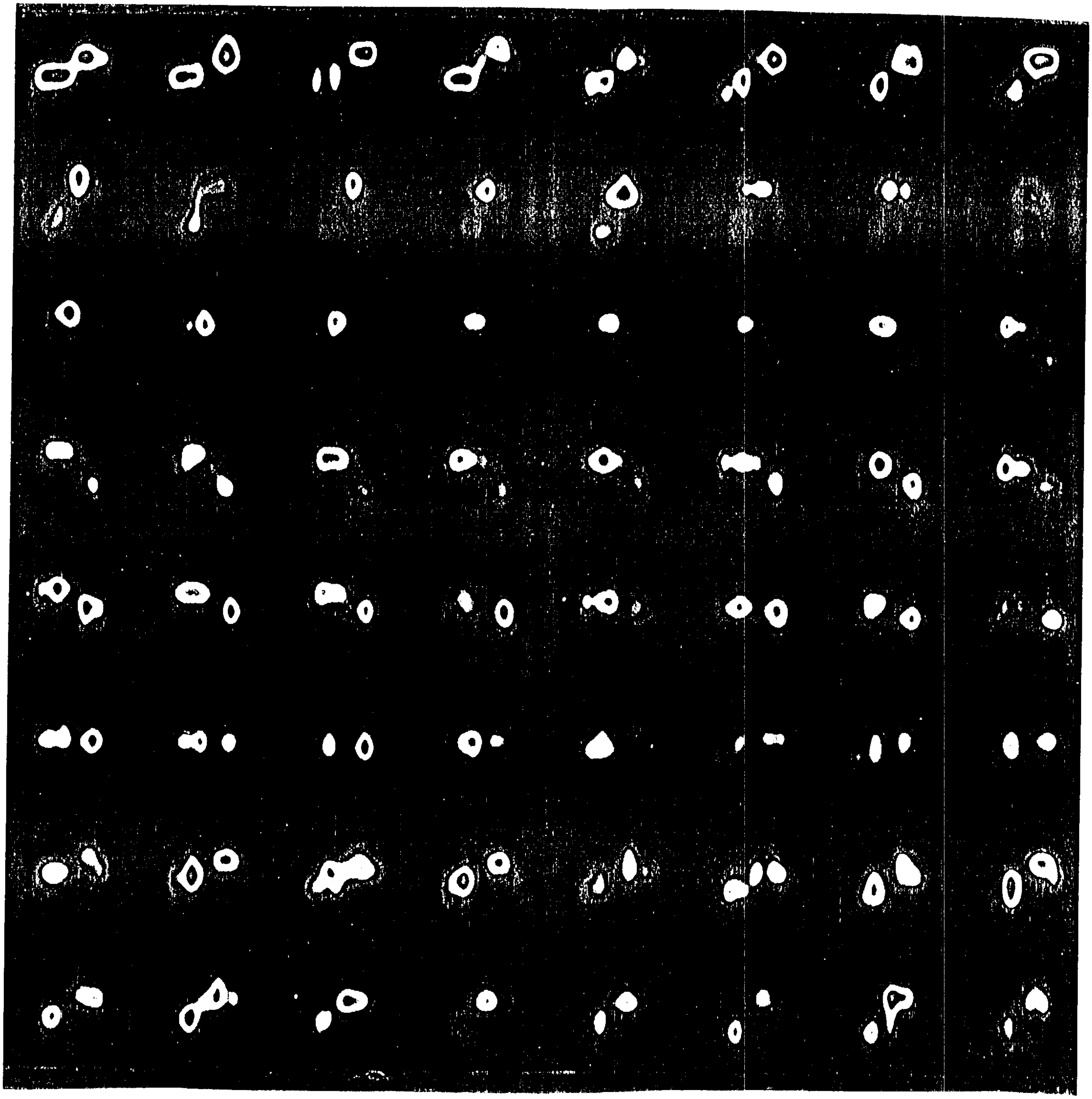
11. The 70-m antenna (DSS 14) of the Goldstone Solar System Radar in California. Radar transmitting and front-end receiving equipment is in the nearest of the three cones at the secondary focus.


Relative Line-of-Sight Speed (m/s)
−40
−20
0"
+20
+40
Goldstone Radar Echoes from Comet Hyakutake
Echo Power (std. devs.)
20
10
0
nucleus
coma
-2
−1
0
+1
+2
Relative Doppler Frequency (kHz)

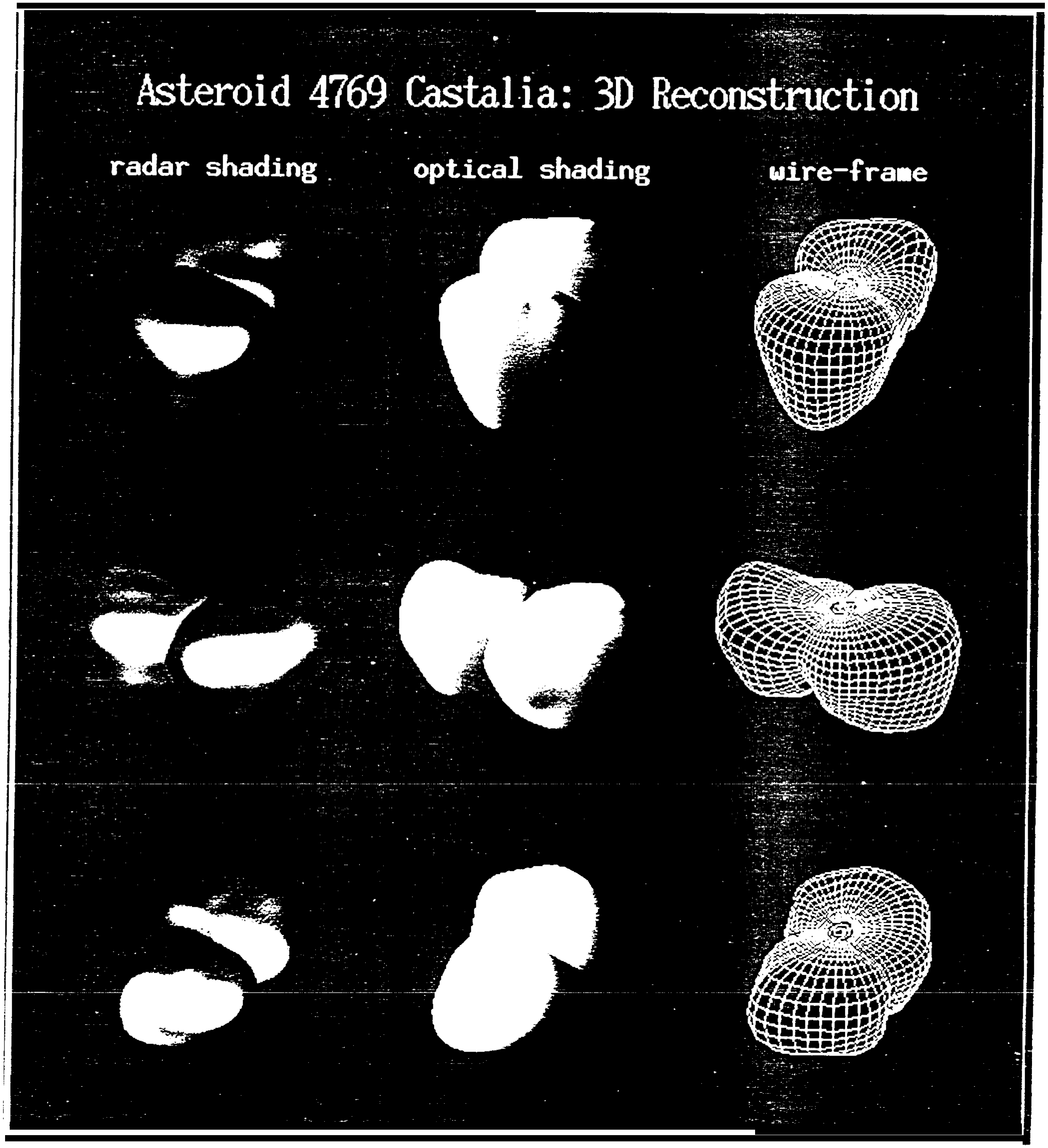
Ostro Fig. 1



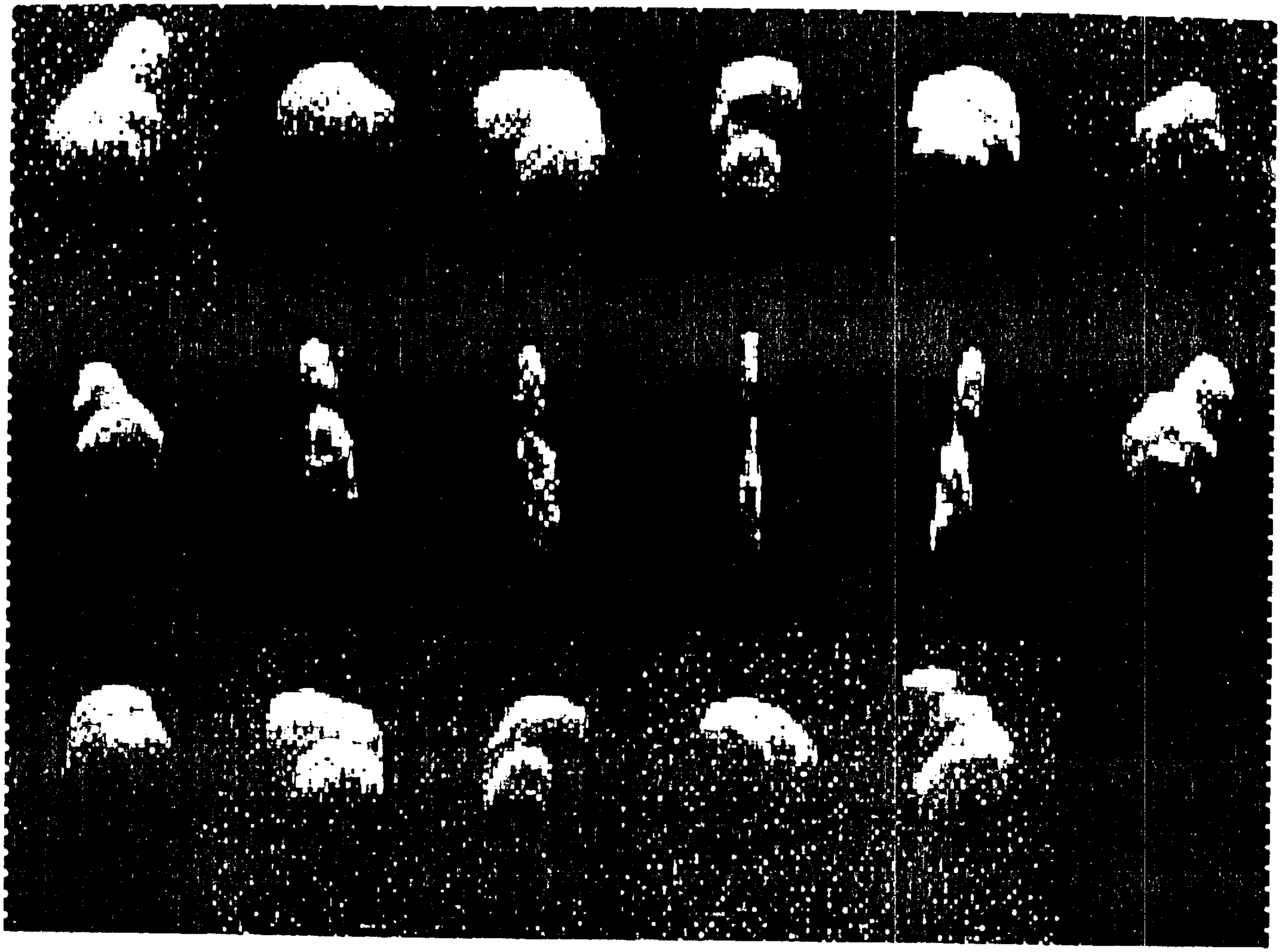
Ostro Fig. 2



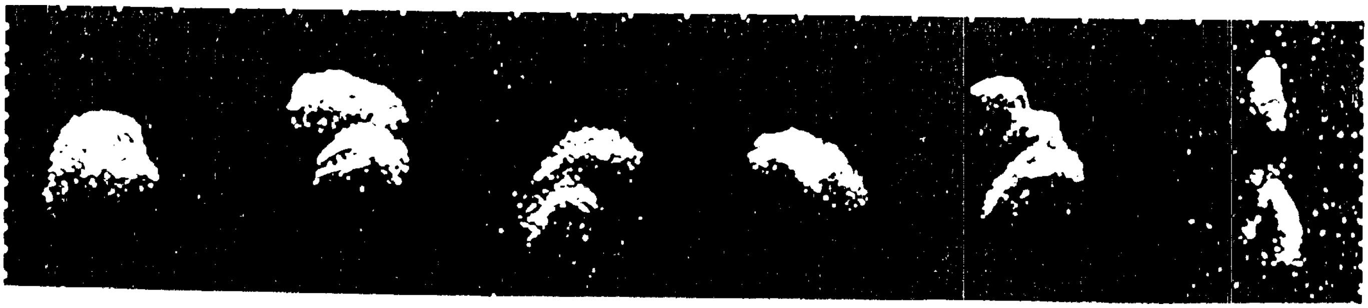
Ostro Fig. 3


Asteroid 4769 Castalia: 3D Reconstruction
radar shading
optical shading
wire-frame

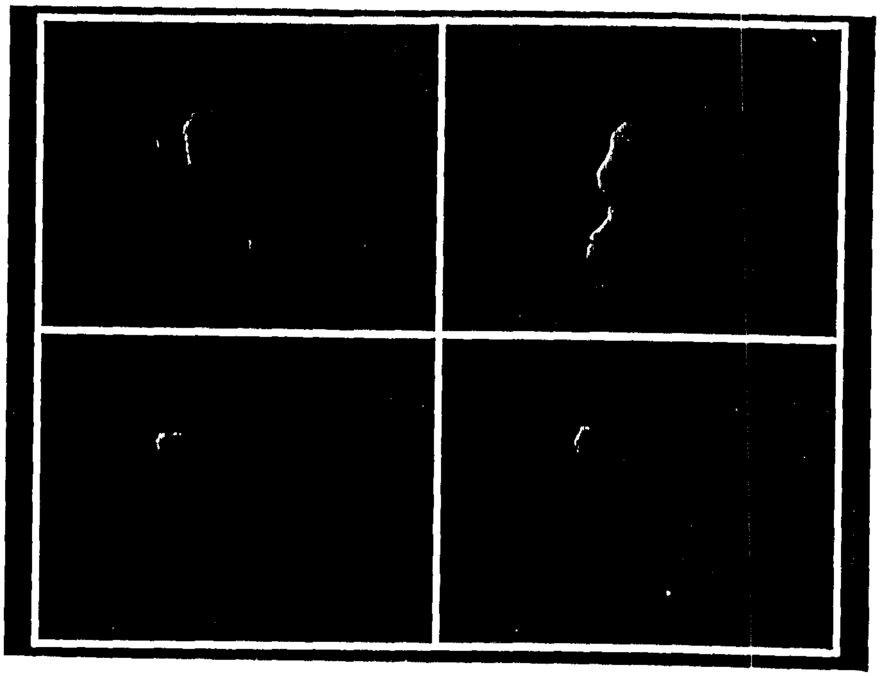
Ostro Fig 4



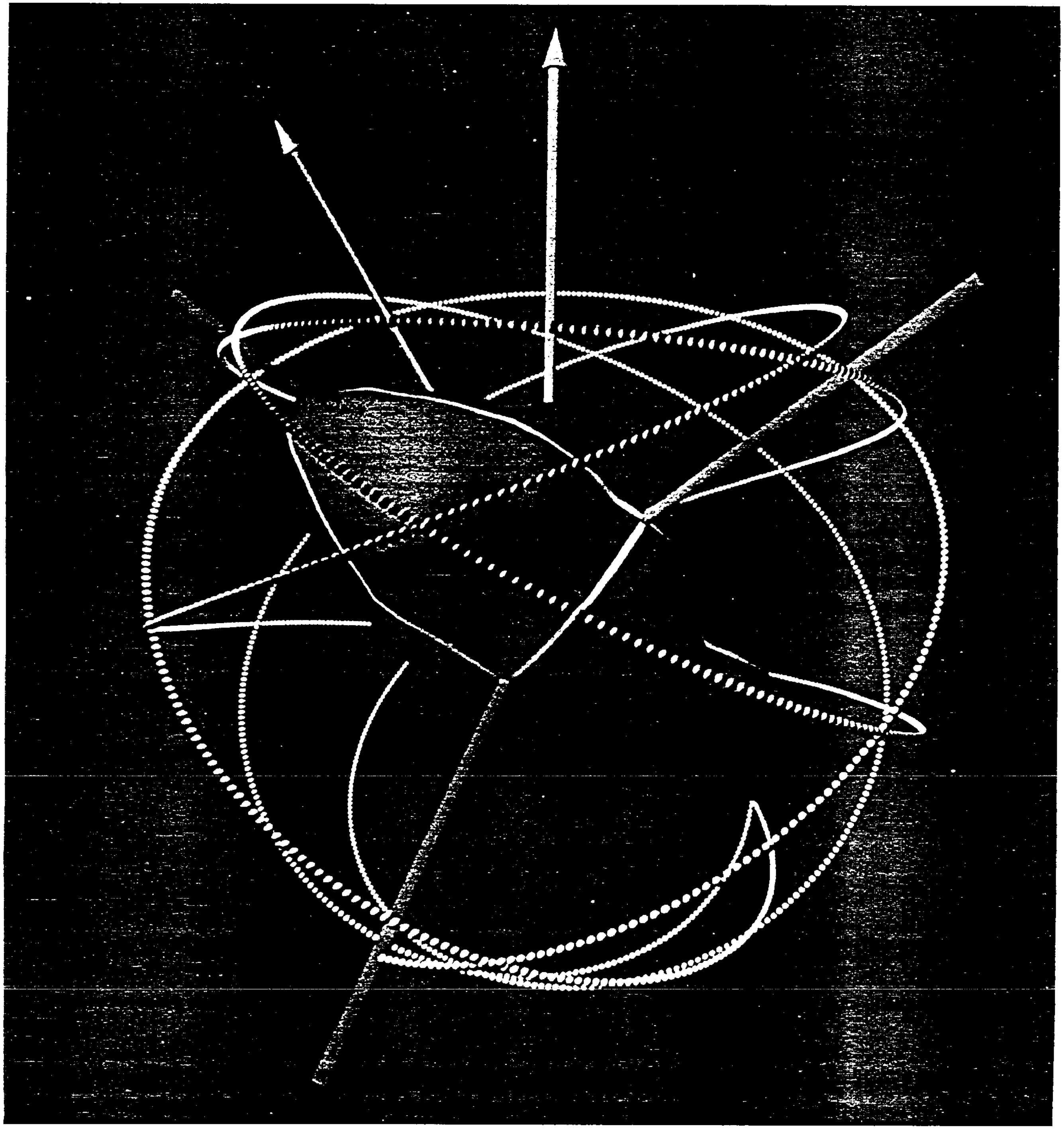
| | | | | | |
|---|---|---|---|---|---|
| 2 | 3 | 4 | 5 | 6 | 7 |
| 8 | 9 | 10 | 11 | 12 | 13 |
| 14 | 15 | 16 | 17 | 18 | 19 |



Ostro Fig. 5



Ostro Fig. 6

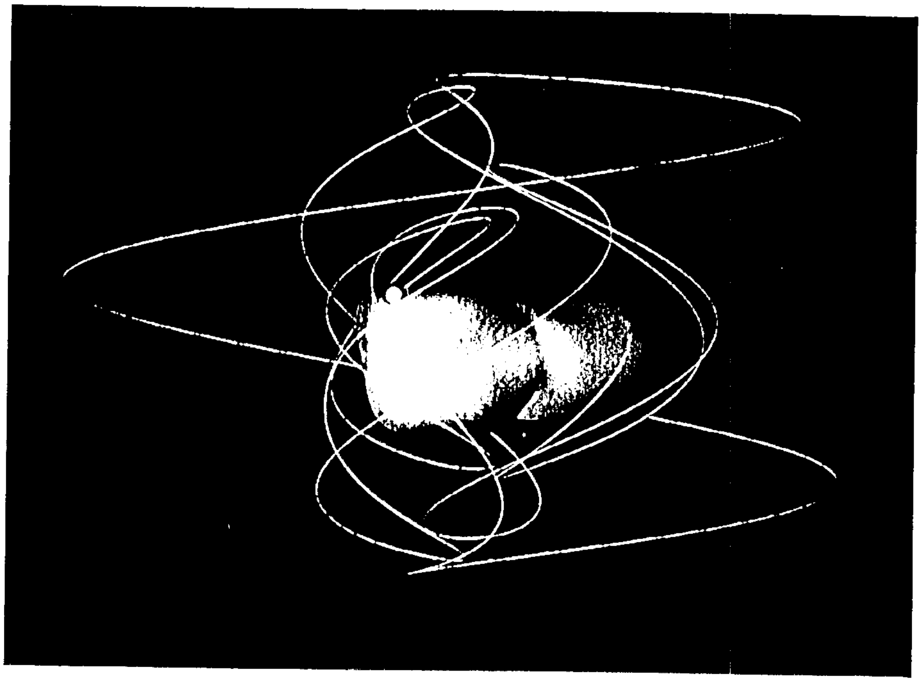


Ostro Fig 7

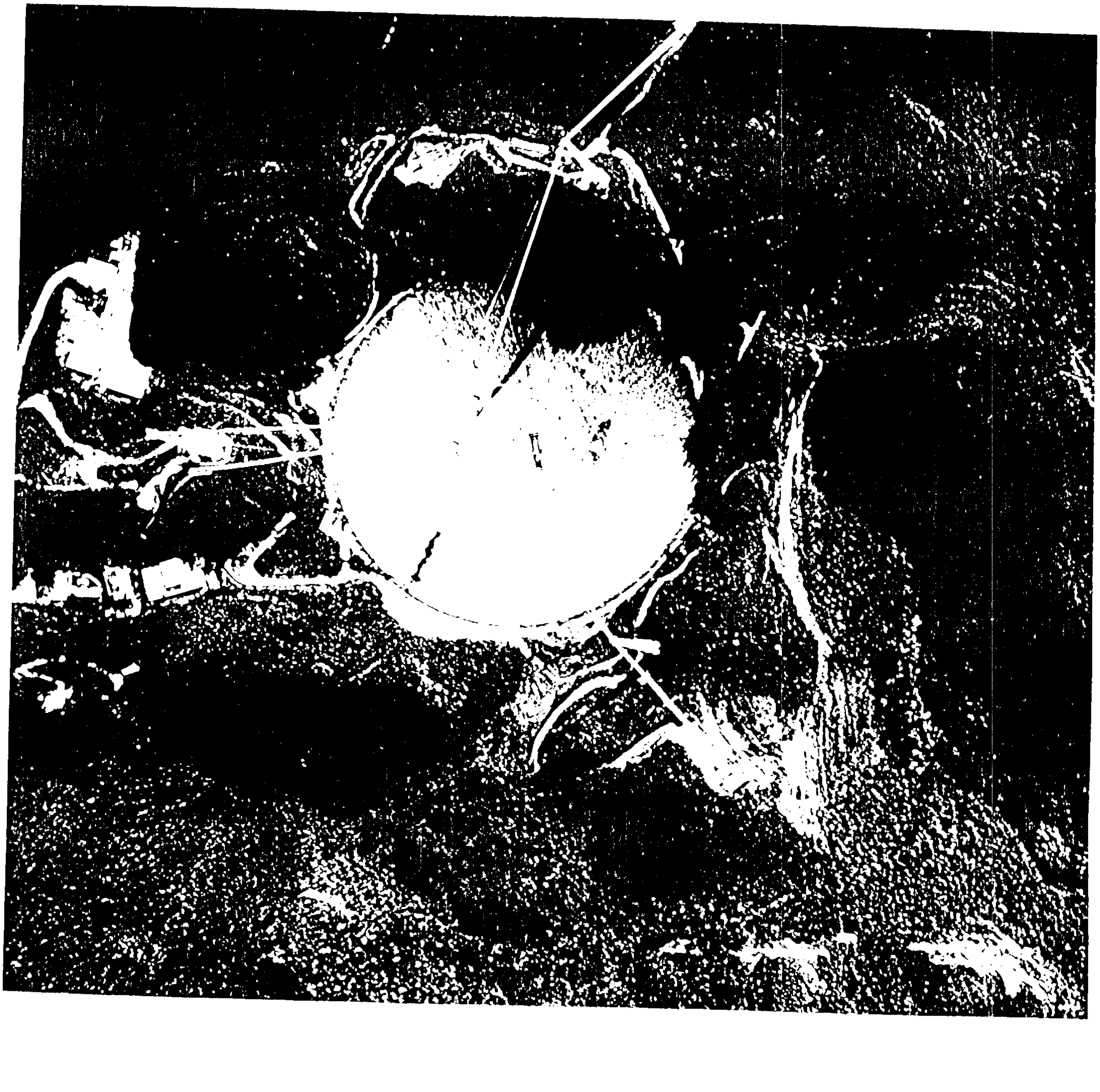
TOP

S. OSTRO

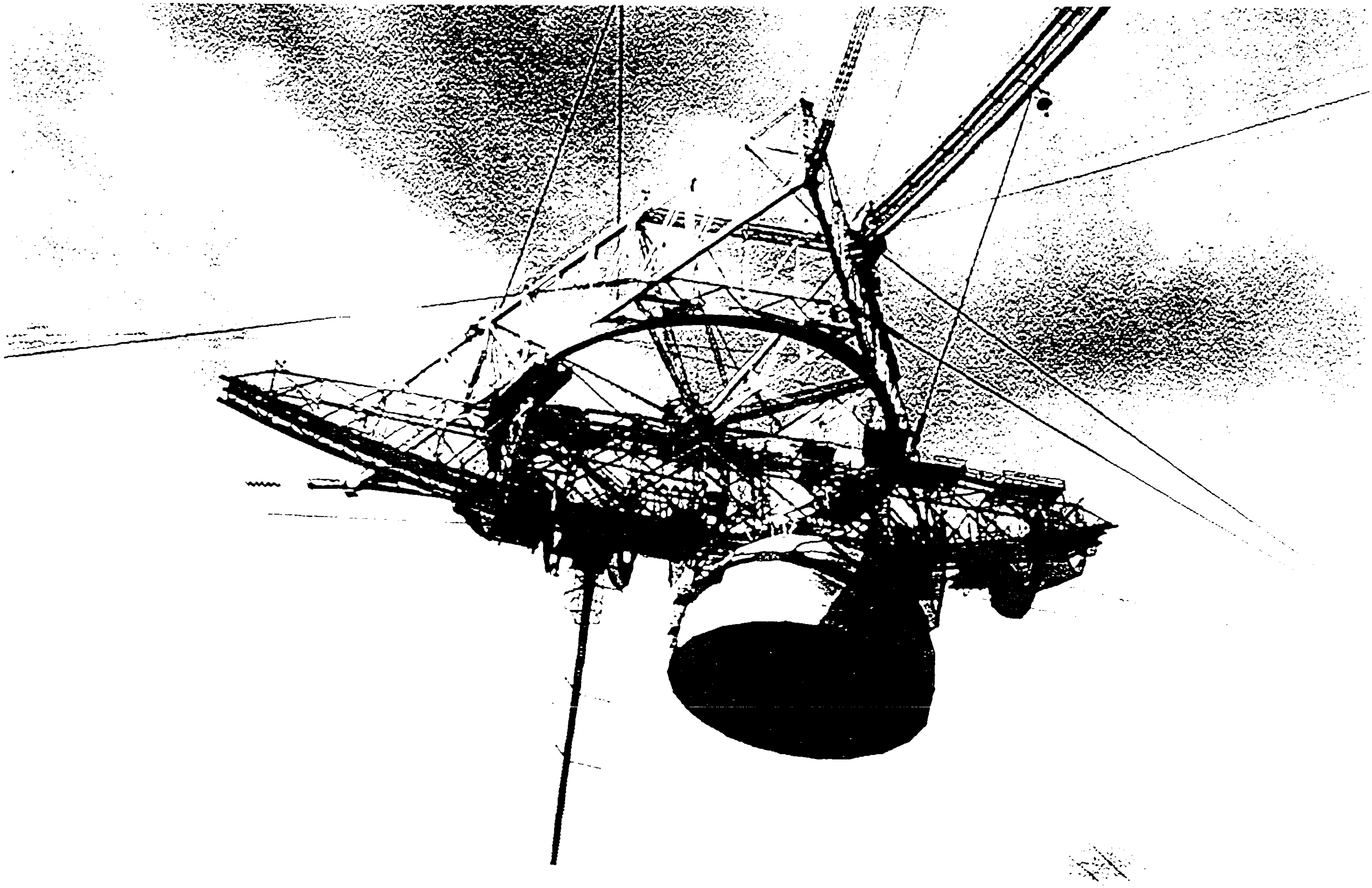
Ostro Fig 8



Ostro Fig. 9



Ostro Fig. 10a



Ostro Fig. 10b

Ostro Fig. 11